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Impacts of telecommuting on time use and travel: A case study of a neighborhood telecommuting center in Stockholm

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ABSTRACT

While telecommuting (TC) research heavily discusses travel impacts of home-based TC, little is known about impacts of working from a neighborhood TC center on travel and non-travel activities and their energy requirements. We conduct a case study on the impacts of the work location (employer's office, TC center, home) on time use and travel using data collected in a neighborhood TC center in Stockholm. Our results show that telecommuters more frequently replaced working from the TC center for working from the more distant employer's office than for working from home. On TC center and home office days, diarists spent less time traveling, and on home office days more time on chores and leisure than on employer office days. When working from the TC center instead of the employer's office, telecommuters frequently used the same or more energy-efficient commute modes, e.g. biking instead of the car, which was feasible because the TC center is in the local neighborhood. However, when working from home, diarists mainly used the car for private travel. Thus, energy savings of TC can be increased by providing energy-efficient transport options or local access to non-work destinations to telecommuters. TC energy impacts depend also on changes to energy requirements for non-travel activities, for space heating/cooling/lighting at all work locations, and systemic TC effects (e.g. residential relocation), which can only be observed in the long term. Thus, future TC assessments should take an even broader perspective in terms of travel and non-travel activities, their energy requirements, and systemic effects.

1. Introduction

Telecommuting (TC) by "working at home or at an alternate location and communicating with the usual place of work using electronic or other means, instead of physically traveling to a more distant work site" (Mokhtarian, 1991, p. 11) promises to reduce physical commuting and associated environmental impacts. Home-based TC (or home office, HO) has been adopted by many companies worldwide and discussed in research for decades. Working from a "local or neighborhood work center" (an office space which is "shared by two or more employers" (Mokhtarian, 1991, p. 4)) also has the potential to reduce physical commuting, while avoiding the deficits associated with working from home (e.g. isolation, lack of focus) (Buffer, 2020; Vaddadi et al., 2020). As the number and variety of office spaces which are shared between workers from different organizations (e.g. co-working spaces, digital work hubs, smart work hubs) and the number of work activities which can be conducted remotely (e.g. due to high-speed Internet connections, cloud-based collaboration solutions, better video conferencing technology) are increasing (Valenduc and Vendramin, 2016; deskmag, 2019; Bieser and Coroamă, 2020), it has become an increasingly viable option for organizations to adopt center-based TC.

The idea that TC (including center-based TC) can reduce energy consumption and greenhouse gas (GHG) emissions associated with physical commuting has been discussed for a long time (Mokhtarian et al., 1995; Höjer, 2002; O'Keefe et al., 2016; Lachapelle et al., 2018). However, telecommuters will spend time saved on commuting on other activities such as private travel or leisure. These substitute activities have their own environmental impacts and can compensate for the

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environmental gains associated with the reduction in physical commuting (a pattern known as the time rebound effect) (Jalas, 2002; Binswanger, 2003; Sorrell and Dimitropoulos, 2008; Brenčič and Young, 2009; Bieser et al., 2019). While several studies have investigated TC impacts on travel (Glogger et al., 2008; Roth et al., 2008; Lachapelle et al., 2018; Tanguay and Lachapelle, 2019), there are fewer studies on TC impacts on time spent on non-travel activities such as leisure or everyday chores, specifically for the case of center-based TC.

Special attention has to be given to transport modes, since their energy and GHG impacts differ strongly. Thus, the potential energy and emission savings through TC differ across regions with different commute modal splits (e.g. commuting by public transport, bike or foot is more common in Sweden than in the US (Richter, 2019; Trafikanalys and Sveriges officiella statistik, 2020)). TC can even be viewed as an additional transport mode that competes in a dynamic system with the physical ones (Hilty et al., 2004).

The aim of this article is to explore the potential and actual impacts of working from a neighborhood TC center or from home on time spent on travel and non-travel activities as well as transport modes used. The results will help to identify those conditions under which (center-based) TC at a larger scale can be a viable approach to reduce energy consumption.

We first summarize related work in the field and derive research questions based on the research gaps identified (Section 2). We answer the research questions using data from a living lab TC center in a residential neighborhood in the south of Stockholm (Section 3). We discuss the travel, non-travel, and potential direct energy impacts of TC in light of the results of this analysis in Section 4 and end with conclusions in Section 5.

2. Related work

In the following, we summarize related work on impacts of home-based TC (2.1) and center-based TC (2.2) on travel. In addition, we summarize work on TC and non-travel activities (2.3), on TC in Sweden and Stockholm (2.4), on the energy impacts of travel and non-travel activities (2.5), and summarize the identified research gaps (2.6).

2.1. Travel impacts of home-based telecommuting

The impact of home-based TC on travel has been studied for decades. Most studies conducted before 2000 focus on North America and Europe (Hamer et al., 1991; Koenig et al., 1996; Roth et al., 2008). TC has gained more attention in Asia in the last two decades (Kim et al., 2012; Kim, 2017; Jaff and Hamsa, 2018; Ma et al., 2019), but research activity in North America also remained high (Hu and He, 2016; Chakrabarti, 2018; Shabanpour et al., 2018; Zhu et al., 2018; Tanguay and Lachapelle, 2019).

Several early studies find that home-based TC reduces travel (e.g. Hamer et al., 1991; Glogger et al., 2008; O'Keefe et al., 2016; Jaff and Hamsa, 2018; Shabanpour et al., 2018); however, in recent years, various analyses indicate that TC leads to an increase in work and non-work trips (e.g. Zhu, 2012; He and Hu, 2015; Hu and He, 2016; Chakrabarti, 2018). A recent study from England (Budnitz et al., 2020) shows that telecommuters conduct more escort, leisure, errand or personal business trips. The authors find that telecommuters are less car dependent than non-telecommuters. Thus, creating local access to non-work destinations can encourage telecommuters to use environmentally-friendly transport modes for non-work trips. A recent study on TC in Sweden (Elldér, 2020) finds that telecommuters conduct fewer and shorter trips, use the car less and active transport modes (biking or walking) more often on TC days than non-telecommuters.

TC impacts can be different for full-day and part-day telecommuters. For example, studies in the US find that full-day telecommuters travel less on TC days, whereas part-day telecommuters only reduce the number of trips during morning rush hours (Asgari and Jin, 2018) but total daily travel time on TC days does not decrease (Stiles and Smart, 2020).

A frequently discussed question is the impact of TC on residential location. Some studies argue that telecommuters live further away from work than non-telecommuters and have higher travel budgets which are reallocated to travel for other purposes when they telecommute (Zhu et al., 2018), others suggest that relocation decisions are mostly driven by factors other than TC (De Abreu e Silva and Melo, 2018; Kim et al., 2012).

TC can also impact travel of telecommuters' household members, e. g. due to increased car availability. Existing studies suggest that if households have at least on car per adult, TC is unlikely to increase car use at the household level (Mokhtarian et al., 1995; Kim et al., 2015). In an early TC study in the Netherlands, Hamer et al. (1991) find that household members perceive an increased "hominess" feeling and travel less when the telecommuter is at home.

2.2. Travel impacts of center-based telecommuting

There are only a few empirical studies on travel impacts of center-based TC. An early study on a TC center project in Washington shows that working from a TC center decreases the number of commute-related vehicle-miles travelled (VMT) but non-commute-related VMT do not change on TC days (Henderson and Mokhtarian, 1996, p. 29). In a study on neighborhood TC centers in California, Balepur et al. (1998) find that VMT and person-miles traveled (PMT) decrease, that commute trips increase due to lunch breaks at home and that on TC days telecommuters increase their use of drive alone modes and their non-work trips. A study conducted in the same project also finds that walking and biking shares increased on TC days compared to non-TC days (Mokhtarian and Varma, 1998). A recent simulation study in Scotland finds that if physical interaction between colleagues is required, a "culture where team members collectively decide on the common worksite is necessary" in order to reduce commuting (Ge et al., 2018, p. 96).

In recent years, new forms of TC centers, specifically co-working spaces, have evolved. Even though co-working spaces differ from conventional TC centers (e.g. they are often used as the main workplace by entrepreneurs or freelancers who rent a workplace on a monthly basis, they aim to create a community and collaboration among co-workers (DeGuzman and Tang, 2011; Yu, Burke, et al., 2019)), they in principle provide the possibility to reduce commuting if they are closer to the employees' homes than their employers' offices (EO). However, existing studies on co-working spaces focus on other aspects, such as different types and locations of co-working spaces (e.g. Kojo and Nenonen, 2016; Mariotti et al., 2017; Wang and Loo, 2017; Fiorentino, 2019).

2.3. Telecommuting impacts on non-travel activities

TC impacts on non-travel activities have been less researched than impacts on travel activities. Both early and recent studies show that shorter commute time (including telecommuting) is associated with more time spent on non-travel activities such as shopping or leisure (Gould and Golob, 1997; Fujii and Kitamura, 2000; Kuppam and Pendyala, 2001; He and Hu, 2015; Paleti and Vukovic, 2017), which is not surprising in view of the 24-hour time budget constraint. Asgari et al. (2016) show that full-day telecommuters spend more time on discretionary activities, and part-day telecommuters more time on maintenance and shopping activities. Asgari and Jin (2017) examine the direction of the causal relationship and find that people who decide to participate in non-mandatory activities (e.g. leisure and maintenance activities) on a given day are more likely to decide to telecommute on that day. In contrast, Rhee (2008), using a spatial equilibrium model, finds that the commute time saved is mainly spent on additional work and not on leisure. Asgari et al. (2019) investigate the impact of TC on the temporal and spatial distribution of activities and find that TC does not have a large effect on the timing and location of non-mandatory activities.

2.4. (Tele-)commuting in Sweden and Stockholm

The main commute transport mode in Sweden in 2019 was the car, followed by public transport (Trafikanalys, 2020). Bastian and Börjesson (2018) find that the mean commuting distance in Stockholm increased between 2004 and 2015, specifically for commutes to job locations outside the city center which are most commonly conducted by car. They also find that “a strategy towards more sub-urban employment clusters is not reducing commuting distances or the car share” and that “to reach the suburban jobs by transit, many workers would need to travel on an indirect route and pass through Stockholm’s crowded inner city stations, because of the radial design of the transit system” (p. 82). Thus, there is a large potential to avoid environmental impacts, congestion and mental burdens caused by commuting through TC from home or from neighborhood TC centers in suburbs of Stockholm.

Existing studies on TC in Stockholm and Sweden indicate that its adoption increased in the last 20 years (Vilhelmson and Thulin, 2016; Statistics Sweden, 2019). These studies mainly focus on home-based TC and we could not find a systematic assessment of center-based TC in Sweden. Searching for TC centers on common TC platforms in Stockholm (e.g. Coworker, 2020; MatchOffice, 2020; Regus, 2020) shows that existing TC centers are mainly located in the city center. Some TC centers outside of the city center are located in the highly-industrialized northwest of Stockholm (e.g. in Kista or Solna) and fewer TC centers are located in the south of Stockholm (the location of the TC center investigated in this study).

2.5. Energy impacts of activities

Environmental assessments of TC usually focus on energy or emission impacts of the changes in travel behavior (Mokhtarian et al., 1995; Glogger et al., 2008; O’Keefe et al., 2016; Shabanpour et al., 2018). However, TC can also change time spent on non-travel activities, which are also associated with energy requirements and energy-related emissions. Every activity has direct and indirect energy requirements. While direct energy requirements are caused by the direct consumption of electricity or fuels during the activity, indirect energy requirements are embedded in the goods and services used to perform an activity, such as the energy required to produce a car or an electronic device (Jalas, 2002; Bieser and Hilty, 2020).

Various researchers investigate direct and indirect energy requirements of everyday activities (Jalas, 2002; Aall, 2011; Jalas and Juntunen, 2015; Nässén and Larsson, 2015; De Lauretis et al., 2017), most of which find that the direct and indirect energy requirements of travel are much higher than the energy requirements of most other activities (Aall, 2011; Jalas and Juntunen, 2015; De Lauretis et al., 2017). However, the energy requirements of transport modes differ significantly. While the direct energy requirements of car travel are high, they are lower for public transport and zero for walking and biking (mobitool, 2016). Also, the relationship between time use and energy inputs is linear for some activities (e.g. driving a car longer increases fuel consumption), but for other activities there is no direct correlation between the energy inputs and the time spent on an activity (e.g. playing the piano) (Jalas and Juntunen, 2015). Thus, if TC leads to an increase in time spent on non-travel activities, the net energy impacts depend on the marginal energy requirements of these activities with respect to the time allocated to them.

2.6. Research gaps and research questions

To summarize, four main research gaps exist:

(1) Most studies focus on travel impacts of TC, and only few studies consider non-travel activities.
(2) No TC studies consider the *energy impacts* of non-travel activities.
(3) Only few studies on impacts of *center-based TC* exist. These are relatively old, focus geographically on the USA, and do not consider non-travel activities.
(4) Only few studies on travel and time-use impacts of TC in Stockholm exist, specifically for center-based TC.

This study contributes to closing research gap (1), (3) and (4) by answering the following research questions using data collected in a TC center in Stockholm:

RQ 1: When people save time for commuting by working from a neighborhood telecommuting center or from home, to what activities do they allocate the time saved?

RQ 2: What transport modes are used on employer office, telecommuting center, and home office days?

In Section 4, we also discuss TC impacts on the direct energy requirements of travel and non-travel activities and thereby address research gap (2) to some extent.

3. Materials and methods

3.1. Telecommuting center living lab

The TC center living lab is a TC center in Tullinge, south of Stockholm, which offers 14 workplaces plus conferencing facilities (e.g. telephone booths, meeting rooms). The aim of the living lab is to investigate the effects of having a professional office space near the participants’ homes on their travel behavior. The space started operation in January 2019 and as of February 2020, 44 people regularly work from there. Most of these participants are employed by an IT company which has its headquarters in Kista, north of Stockholm (Fig. 1). A one-way commute by car or public transport between Tullinge and the company’s headquarters takes at least 40 min and usually longer due to congestion. Since living in proximity to the TC center was a requirement for participating, all participants from this company save commuting time on days when they work from the TC center instead of the headquarters. The following analysis is based on the data collected from 20 participants of the TC center living lab who work for this company.

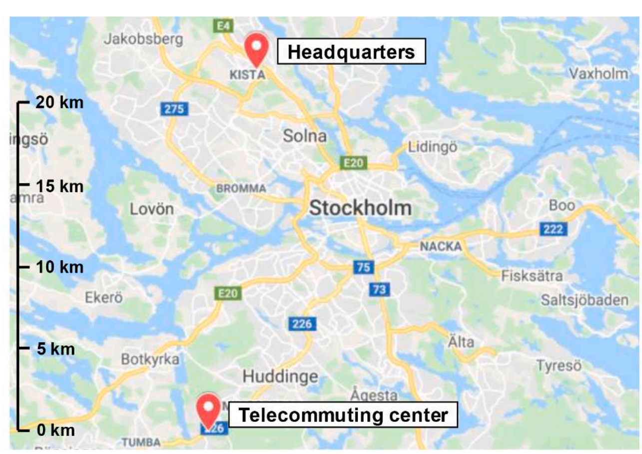

Fig. 1. Location of the headquarters of the IT company in Kista and the telecommuting center in Tullinge.

Table 1
Number of diarists by demographic and socio-economic characteristics.

Gender		Age				Hhld. size			#Children in hhld.				Residence			#Cars		
Female	Male	45-50	50-55	55-60	60-65	2	3	5	0	1	2	3	Appartment	Townhouse	Villa	1	2	4
5	15	3	4	9	4	13	5	2	12	5	1	2	1	6	13	10	9	1

3.2. Sample population

Table 1 provides an overview of important demographic and socio-economic characteristics of the 20 participants. All diarists are at least 45 years old and live with at least one other person in the household. A closer look at their job types (not provided in the table) shows that most of them work in knowledge-intensive jobs (e.g. managers, IT/engineering/business professionals). All diarists live in the current residence since at least 10 years, most even more than 20 years.

3.3. Analysis of time-use diaries

These participants filled out a survey on their work and travel patterns before working from the TC center and kept a time-use diary for three weeks (between September and November 2019) while the TC center living lab was ongoing. In the diary, they indicated which activities they performed in 15-min intervals and how much time they spent in 11 different transport modes. The diary distinguished the following activities:

- work (differentiated into work from TC center, home, EO, and meetings outside the office)
- travel
- everyday chores
- leisure

For analyzing the frequency of working from the TC center or from home, we excluded days when the diarists did not work (295 diary days over all participants). For analyzing time spent on activities on typical workdays we also excluded diary days if the total recorded time was less than 8 h (low-quality record), days for which work was less than 4 h or travel was more than 4 h (atypical workdays), and days with more than one work location (244 diary days).

Some answers are inconsistent because travel time by transport modes and total daily travel time were covered by different questions in the survey. We calculated the “share of travel time by transport mode” based on responses to “travel time by transport mode” and calculated “absolute time spent in transport modes” based on the “share of travel time by transport mode” and responses to “total daily travel time”.

We also compared commute transport modes on EO and TC center days. Due to the fact that time-use diaries only asked for daily time spent in transport by mode, we had to infer the commute transport modes. While this approach introduces some uncertainty, it allows us to observe some major trends about impacts of working from the TC center on commute transport modes.

We used the survey and time-use data to compare numbers of workdays by work location before and during working from the TC center as well as time allocation, travel time by transport mode, and commute transport modes when people worked exclusively from the EO (long commute), from the TC center (short commute), or from home (no commute). To do so, we use graphical data analysis and a mixed-effects model. In the mixed-effects model, the dependent variables are either daily time spent on travel, work, chores or leisure ($t_{activity}$) or daily time spent in car transport, public transport, biking or walking or in other modes (t_{tr_mode}). The independent variables reflect whether the respective day was a TC center day or not (IS_tcc_day), or a HO day or not (IS_ho_day) (EO days are the base case). We also included a random effect to control for differences between diarists ($U_{diarist}$), because we know that other characteristics of diarists influence daily time use, which are, however, not the focus of this study.

$$t_{activity/tr\_mode} = \beta_0 + \beta_1 IS\_tcc\_day + \beta_2 IS\_ho\_day + U_{diarist}$$

Parts of the analysis of time allocation and time spent in transport modes – which we complemented with more detailed data analysis – have been used in another study to develop and demonstrate a conceptual framework of environmental effects of working from a TC center (Vaddadi et al., 2020).

4. Results

4.1. Number of workdays by work location

Table 2 shows the share of workdays worked from different work locations before (based on a self-assessment) and during participating in the TC living lab (based on time-use diaries).

Fig. 2 shows how the share of workdays by work locations among diarists changed before and during the TC center living lab. It shows that most diarists mainly substituted working from the EO with working from the TC center (reduction of commute). Only one diarist mainly substituted working from home with working from the TC center (increase of commute). Some diarists mainly substituted working from the EO with working from home (reduction of commute).

Table 2
Share of total workdays by work location before and during the TC center living lab. “Other” days are weekdays with several or other work locations. The adoption of home office before working from the TC center is based on a self-assessment of diarists and did not include “other” days. The data also include atypical workdays (e.g. short work time) and low-quality diary days to show the adoption of working from the TC center across all workdays.

Work location	Employer office (long commute)	TC center (short commute)	Home (no commute)	Other	Comment
Before TC center living lab	86%	n/a	14%	n/a	Based on self-assessment
During TC center living lab	57%	17%	12%	14%	Based on time-use data

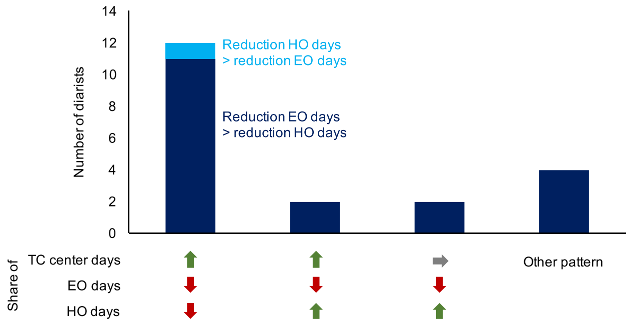

Fig. 2. Change in share of workdays by work location before and during participating in the TC center living lab. "↑" means the share increased, "" means the share decreased, "→" means the share remained stable. "Other patterns" are, for example, increase in share of days at other work locations.

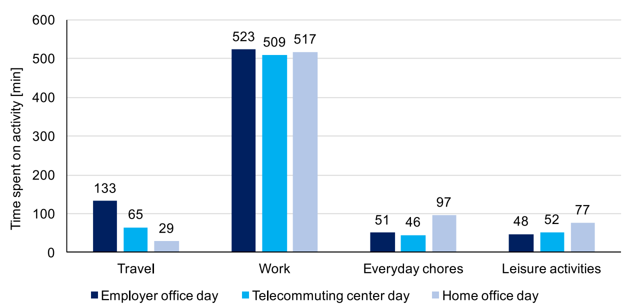

Fig. 3. Average daily time spent on activities by work location.

Table 3
Estimations of mixed-effects model for time spent on activities ($t_{activity} = \beta_0 + \beta_1 IS\_tcc\_day + \beta_2 IS\_ho\_day + U_{diarist}$). Signif. codes: 0.001: ***; 0.01: **; 0.05: *.

Comparison	Travel	Work	Everyday chores	Leisure
TC center day - employer office day (β_1)	−70.73***	−1.90	10.94	16.74
Home office day - employer office day (β_2)	−102.00***	15.95	41.28***	26.80*

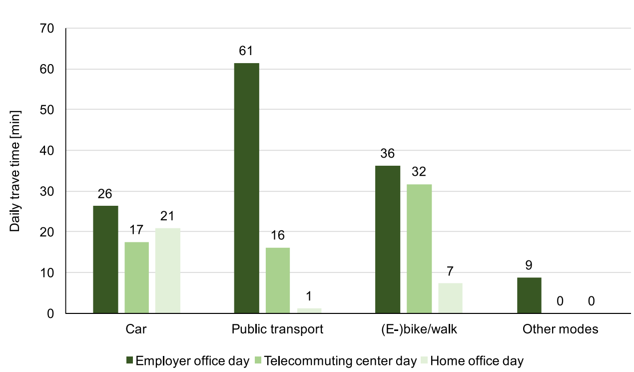

Fig. 4. Daily travel time per workday across transport modes by work location.

Table 4
Estimations of mixed-effects model for time spent in transport modes ($t_{tr\_mode} = \beta_0 + \beta_1 IS\_tcc\_day + \beta_2 IS\_ho\_day + U_{diarist}$).. Signif. codes: 0.001: ***; 0.01: **; 0.05: *.

Comparison	Car	Public transport	(E-)bike/ walk	Other modes
TC center day - employer office day (β_1)	−5.99	−52.07***	−9.74**	−3.69**
Home office day -employer office day (β_2)	1.45	−66.47***	−33.26***	−0.61

4.2. Time spent on activities by work location

Fig. 3 shows the average daily time spent on activities during the TC center living lab by work location and Table 3 shows the estimators of the mixed-effects model.

On TC center days, people spent on average roughly half as much time *traveling* as on EO days. On HO days, people spent even less time traveling. The mixed-effects model shows that these differences are significant. Average time spent on *work* does not differ significantly by work location. The average time spent on *everyday chores* and *leisure* is greatest on HO days and roughly equal on EO and TC center days. The mixed-effects model shows that the differences in time spent on *everyday chores* and *leisure* between EO and HO days are significant.

4.3. Average travel time across transport modes by work location

Fig. 4 shows the average daily travel time (commute + private travel) across transport modes during the TC center living lab and Table 4 shows the estimators of the mixed-effects model.

Average time spent on *car travel* is longest on EO days and shorter on TC center days. On HO days, *car travel* is longer than on TC center days. Since there is no commute on HO days, *car travel* is done for private purposes only. However, the mixed-effects model shows that the differences are not significant. The time spent in *public transport* is longest on EO days, shorter on TC center days, and almost zero on HO days. The mixed-effects model shows that these differences are significant. The time spent on *biking and walking* is roughly equal on EO and TC center days and shorter on HO days. The mixed-effects model shows that these differences are significant.

4.4. Commute transport modes

Fig. 5 shows the share of workdays by commute transport modes and work location during the TC center living lab. The data reported on some

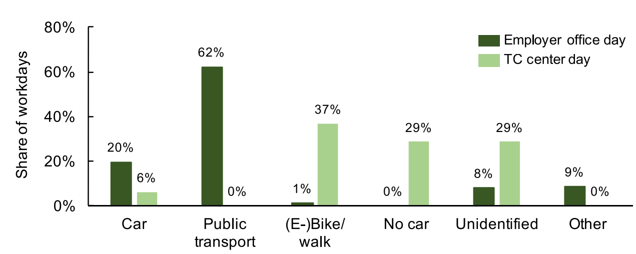

Fig. 5. Share of workdays across all diarists by commute transport mode and work location on that day. "No car" means the diarist commuted by public transport, (e-)biked, or walked. "Unidentified" means that considerable transport times were reported for car, public transport, and/or (e-)bike/walk on the diary day.

diary days did not permit clear identification of the commute transport mode. These observations are indicated as "unidentified". The data reported on some diary days merely showed that the car was not used; however, it was not clear whether the diarists commuted by public transport, (e-)bike, or foot to the TC center. These observations are indicated as "no car". The data shows that commuting by car and public transport is less common and by bike or foot more common on TC center days than on EO days.

5. Discussion

5.1. Adoption of working from home or the TC center

Even though data captured before and during working from the TC center is not entirely comparable, because the data collection before working from the TC center did not consider "other" days and was based on a self-assessment, it indicates that diarists substituted working from the TC center more frequently for working from the EO than for working from home. As the commute distance to the EO is many times higher than the commute distance to the TC center, it is likely that the total commute distance decreased during the TC center living lab.

However, we cannot compare the amount of work from "other" locations (e.g. several work locations on one day, part-day TC, which could increase work-related travel) before and during working from the TC center. Also, there is the possibility that on TC center days diarists went home during lunchtime and back to the TC center afterwards (e.g. as found by Balepur et al. (1998)), which would double the number of commute trips on these days. Therefore, it is also important to look at the average daily time spent on travel (and non-travel) activities by work location.

5.2. Travel on employer office, TC center, and home office days

5.2.1. Travel time

Average travel time (commute + private travel) is significantly shorter on days when diarists worked from the TC center instead of the EO. This indicates that, even if diarists went home during lunch time on TC center days, these additional commute trips plus additional travel for other purposes do not exceed the saved commute time on TC center days. On HO days, travel time is shortest, also showing that on these days, diarists did not use the total saved commute time for travel for other purposes. This result is in line with the previous studies of travel impacts of working from TC centers (e.g. Henderson and Mokhtarian, 1996; Balepur et al., 1998; Ge et al., 2018) and with results of studies of home-based TC, which find a reduction of total daily travel time on TC days (e.g. Lachapelle et al., 2018).

Our study is not directly comparable with studies considering associations between telecommuting, residential relocation, and travel (Kim et al., 2012; Zhu, 2012), nor with studies considering the travel of telecommuters' household members (Kim et al., 2015) because our data is from 3-week time-use diaries and we did not collect data from other household members.

5.2.2. Transport modes used

On EO days, public transport was the preferred commute transport mode, followed by car transport. On TC center days, some diarists switched to less energy-intensive transport modes (from car to public transport, biking, or walking; or from public transport to biking or walking) or used the same transport modes. There is no indication that working from the TC center induced a major shift to more energy-intensive transport modes (e.g. from public transport to car).

In contrast, the TC center study in California showed that telecommuters increasingly used drive-alone modes on TC days (Balepur et al., 1998). Also, the TC center study in Washington showed that center-based telecommuters mainly used private vehicles to commute to the TC center (Henderson and Mokhtarian, 1996). A possible explanation is that both studies were conducted in the USA, where the average distances from the diarists' homes to the centers were much greater than in our case. The TC center in our case study is located close to the diarists' homes, which makes walking or biking from home to the TC center possible.

If we consider total daily travel (commute + private travel), on TC center days diarists spent significantly less time in public transport than on EO days. This difference can be explained by the fact that public transport is the preferred commute transport mode on EO days.

On HO days, diarists spent almost no time in public transport. If travel on these days occurs (which is private travel because there is no commute on HO days), diarists mainly use the car, bike or walk. In fact, average time spent on car travel is slightly higher on HO days than on TC center days. This observation, even though this difference is not significant, and the fact that time spent on everyday chores is highest on HO days can indicate that diarists shift chore activities which induce car travel to HO days (e.g. going shopping). One approach to counteract such an effect would be to offer sustainable transport options (e.g. ride sharing, bike sharing) and delivery services to telecommuters, or to create local access to non-work destinations as suggested by Budnitz et al. (2020).

Time spent biking and walking was lower on HO than on EO and TC center days. This could indicate that bike or foot travel is somehow related to work routines outside the home (potentially due to walking or biking between home, public transport stops, the EO and the TC center).

5.3. Non-travel activities on employer office, TC center, and home office days

Time spent on *everyday chores* and *leisure* is higher on HO days than on EO or TC center days. As described above, a possible explanation for this is that telecommuters intentionally shift these activities to HO days. Work time is similar on all types of days, potentially because work times are determined in employment contracts. This result confirms the results of most studies of non-travel impacts of TC (Kuppam and Pendyala, 2001; He and Hu, 2015; Paleti and Vukovic, 2017), except for one which finds that the commute time saved is mainly used for additional work (Rhee, 2008).

5.4. Direct energy impacts of changes in time spent on travel and non-travel activities

From a time-use perspective, direct energy impacts of TC depend on changes in time spent on travel and non-travel activities and their direct energy requirements.

Our analysis showed that time spent travelling is highest on EO days, lower on TC center days and lowest on HO days. However, the direct energy impacts of travel depend on the transport modes because transport modes significantly differ in their direct energy requirements (mobitool, 2016). Direct energy requirements are highest for car travel, lower for public transport and zero for biking or walking. Thus, the direct energy savings due to reduced commuting are higher for people who exclusively commute by car than for public transport commuters, and zero for bikers and pedestrians. Therefore, TC strategies should obviously aim at reducing motorized transport and encourage telecommuters to switch to non-motorized transport modes.

We roughly estimated direct energy requirements per hour (MJ/h) of travel and total daily travel energy requirements (MJ) based on mobitool (2016) using average daily travel times (Fig. 3) and modal splits (Fig. 4) as observed in the TC center case study on EO, TC center, and HO days. For this estimation (see Fig. 6), we had to work with average speeds of transport modes (Johnson et al., 2016) because mobitool provides energy requirements per distance covered.

In the TC center case study, travel on HO days has the greatest direct energy requirements per hour because the car has by far the highest modal share on these days. Direct energy requirements per hour on EO

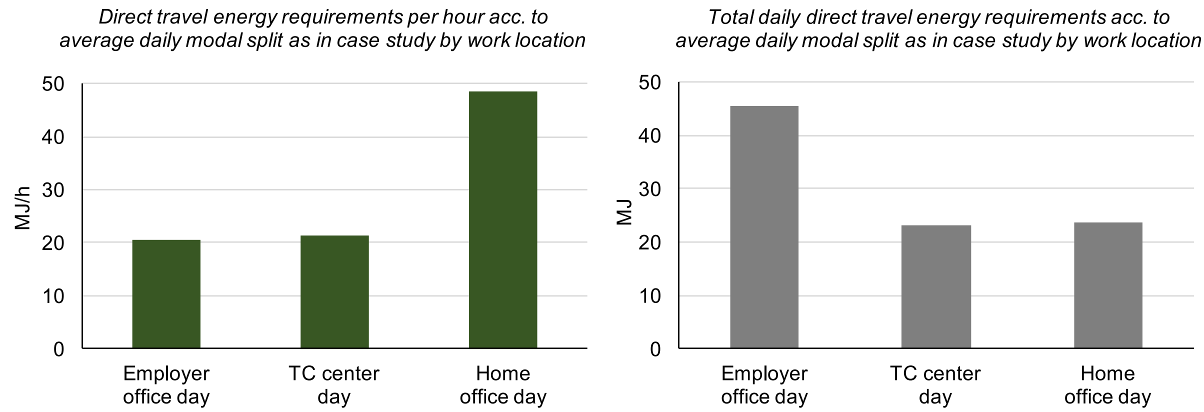

Fig. 6. Direct travel energy requirements per hour according to the observed average modal split in the TC center case study by work location (left) and total daily direct travel energy requirements considering the average modal split in the TC center case study by work location (direct energy requirements per hour * total daily travel time).

and TC center days are similar. Still, as travel time is significantly smaller on TC center and HO days than on EO days, total direct energy requirements for travel are lower on TC days. Total direct energy requirements on HO days and TC center days are similar, even though total travel time is significantly smaller on HO days, because the car has by far the highest modal share on HO days.

Time spent on leisure and everyday chores was higher on HO days than EO and TC center days. Since various studies have shown that the (marginal) direct energy requirements of most non-travel activities are lower than those of travel activities (Aall, 2011; Jalas and Juntunen, 2015; De Lauretis et al., 2017), there seems to be a potential for direct energy savings if TC leads to a substitution of travel activities with non-travel activities. However, non-travel activities with high (marginal) direct energy requirements exist, e.g. personal care or food preparation due to energy-consumption for cooking appliances and heating water for personal hygiene (Druckman et al., 2012; De Lauretis et al., 2017; Yu, Zhang, et al., 2019). In fact, it is plausible to assume that food preparation at home increases through HO. However, this effect needs to be compared to changes in direct energy requirements for food preparation at places where telecommuters eat when working from the EO or the TC center (e.g. cafeteria), which is difficult to assess. Also, TC can increase direct energy consumption for heating, cooling and lighting the home or the TC center (Vaddadi et al., 2020). Mokhtarian et al. (1995) summarize early studies which consider household energy impacts of TC and conclude that increases in residential energy consumption account for 11–25% of travel energy savings. However, only if people actually reduce heating energy consumption when they are not at home (e.g. by manually turning off heaters before leaving the dwelling) does increased occupancy lead to an increase in heating energy consumption. In some cases, increased occupancy can even reduce heating energy consumption due to the body heat of occupants (Hinchey, 2019). To mitigate a potential increase in space-related energy demand due to TC practices, it is important that employers, when adopting TC, reduce their office space and associated energy consumption for heating, cooling and lighting (e.g. through shared workplace concepts). Still, for a final assessment of energy impacts of TC more detailed data on types of chore and leisure activities performed, use of energy-consuming goods and services to perform these activities and energy requirements for heating, cooling and lighting at all work locations is required.

Also, if TC is adopted at a larger scale (as some authors predict as a result of the measure taken during the COVID-19 pandemic, e.g. Baert et al., 2020; Bartik et al., 2020), this could lead to a more fundamental change in the nature of work and private activities including the locations where they take place (Vaddadi et al., 2020). For example, if a telecommuter expects to only work occasionally from the EO in future, he/she might reconsider his/her common places to conduct leisure activities or chores (e.g. gyms or grocery stores closer to home or the TC center). Thus, the impact of a large-scale adoption of TC on travel, time use and associated direct energy requirements depends on the interplay between the preferences of individuals, the requirements placed on individuals by their employer and their type of work (e.g. need for physical meetings), and the possibilities (e.g. in terms of location) for conducting work, leisure, chore and travel activities available to individuals. In an early study, Höjer (2000) argues that if people become better "telecommunicators" over time (i.e. they improve their skills in communicating at a distance) in combination with a shift toward network organizations, then this changes the preconditions for TC, and its impact on travel behavior can change as well. More research on such systemic effects is required in order to identify policies (e.g. for TC or urban planning) which allow to harness the potential of TC for energy savings.

5.5. *Limitations*

The analysis is based on cross-sectional data which allows to compare time allocation on days with different work locations or times spent on commuting. However, it does not allow to compare time allocation of individuals before and after adopting TC. Thus, we cannot derive conclusions about the causal effect of TC on time-use and travel patterns (e.g. as could be done with the Solomon four-group design (Lavrakas, 2008)). Conducting pre-post comparisons is crucial because previous studies have shown that telecommuters behave differently than non-telecommuters (He and Hu, 2015). Also, interactions between time use on weekdays and weekends exist and are out of scope in this study. If, for example, people manage to do more housework on weekdays due to working from home or the TC center, they might spend more time on leisure travel on weekends. Also, on EO days, private activities such as library visits, meeting friends or shopping could be combined with commute trips. In this case working from the TC center or from home can also induce additional trips. Further collection of full-week time-use data before and after the adoption of the TC would be necessary to examine these effects.

We did not control for diarists' demographic or socio-economic characteristics due to the small sample size and because diarists have similar characteristics. The behavioral responses to adopting TC can be different for individuals with a different background (e.g. job starters). Thus, the results may not be generalizable to a larger population.

Although the diarists kept the travel diaries carefully, quality differences between diaries were observed. Also, individuals might have different understandings of the activity categories. In general, diarists captured work and travel time more carefully than time spent on chores or leisure.

Further limitations are due to constraints in data collection: We had to exclude days with multiple work locations from the analysis of the diaries, and the study does not cover full 24-hour days.

Finally, indirect energy impacts and systemic effects of TC (e.g. due to a large-scale adoption of TC) were outside the scope of this work, but are considered relevant (Ge et al., 2018).

6. Conclusions

To explore how working from a neighborhood TC center impacts time-use and travel patterns, we conducted a case study using data from a TC center living lab in a residential neighborhood in Greater Stockholm. Our results show:

- Diarists more frequently replaced working from the TC center for working from the more distant EO than for working from home.
- Time spent traveling on TC center days was significantly shorter than on EO days and shortest on HO days.
- When diarists worked from home, they spent more time on everyday chores.
- Time spent on work was less affected by the work location.

An analysis of commute transport modes showed that some diarists used the same commute transport modes or switched to less energy-intensive ones (e.g. from car to biking or walking) on TC center days, and we did not find any indication that working from the TC center led to a shift to more energy-intensive commute transport modes. This shows that offering workplace facilities in a local neighborhood can facilitate use of energy-efficient transport, as telecommuters will walk and bike to work. However, if travel for private purposes was conducted when working from home, diarists mainly used the car. One approach to counteract such an effect would be to actively offer sustainable transport options (e.g. ride sharing, bike sharing) or delivery services to telecommuters.

Whether TC brings about net direct energy savings depends largely on TC-induced changes to (1) time spent in transport, (2) use of transport modes, (3) the substitute non-travel activities and their marginal direct energy requirements, and (4) the direct energy requirements for heating, cooling and lighting at all work locations (EO, TC center, and HO space). In order to increase energy-savings, corporate TC strategies should aim at reducing telecommuters time spent in transport, in particular motorized transport, and the office space required.

Since we conducted an exploratory study based on data from a small sample, the results should only be generalized with great caution. Our analysis is based on cross-sectional data which does not allow to compare changes in time-use and travel patterns before and after the adoption of TC as well as interactions between time-use and travel patterns on weekdays and on weekends. Future assessments of time-use, travel and energy impacts of TC should take a broader perspective in terms of the activities and weekdays considered, and the sample population.

Finally, systemic effects of a larger adoption of TC can lead to fundamental changes in travel habits and locations of activities (e.g. telecommuters might choose a gym closer to home). Including such systemic effects in the assessment of TC could reveal under what conditions TC can be a viable model to reduce environmental impacts associated with lifestyles, take pressure off transport systems, and increase the well-being of workers.

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